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In this project, we analyzed the effectiveness of alternative search control strategies for automatic plan generation. We completed a detailed empirical study of control strategies for partial-order causal-link planners, identifying the relevantadvantages and disadvantages of both strategies in the literative and novel stratagies. We also developed search control heuristics for conditional planning, and demonstrated their effectiveness. Finally, we developed techniques for generating monitors during planning, without incurring excessive overhead.

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Final Technical Report

Principal Investigator:	Dr. Martha E. Pollack
Institution:	Department of Computer Science University of Pittsburgh Pittsburgh, PA 15260
Email:	pollack@cs.pitt.edu
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1 Introduction

This document summarizes the research conducted on the AFOSR-supported project "Search Control for Automatic Plan Generation", Contract F49620-96-1-0403 during the period between Aug. 1, 1996 and Jan. 31, 1998 (18 months). The goal of the project has been to analyze the effectiveness of alternative search control strategies for automatic plan generation and to investigate the interactions between search control strategies and other aspects of the planning architecture. Our efforts were focused on developing strategies for:

- search control in partial-order causal-link planning;
- search control in conditional planning;
- monitor-establishment in dynamic planning, with an emphasis on the interaction between monitoring and the efficiency of planning.

In addition, early in the project we completed some relevant work that had been begun prior to the project start-date, involving search control for planners operating in domains in which actions have explicit costs associated with them.

This report is organized around these topics. We briefly describe the work we did on each of these topics, followed by a list of project-sponsored publications, which provide more details of the work. Copies of these publications are included as an appendix to this report.

2 Search Control for Partial-Order Causal Link Planning

Much of the current research in plan generation centers on partial-order causal link (POCL) algorithms, which descend from McAllester and Rosenblitt's [9] SNLP algorithm. POCL planning involves searching through a space of partial plans, where the successors of a node representing partial plan P are refinements of P. As with any search problem, POCL planning requires effective search control strategies.

In POCL planning, search control has two components. The first, *node selection*, involves choosing which partial plan to refine next. Once a partial

plan has been selected for refinement, the planner must then perform *flaw selection,* which involves choosing either a threat to resolve or an open condition to establish.

Over the past few years, several studies have compared the relative efficiency of alternative flaw selection strategies for POCL planning and their extensions [11, 8, 13, 6, 18]. These studies have been motivated at least in part by a tension between the attractive formal properties of the POCL algorithms, and the limitations in putting them to practical use that result from their relatively poor performance. To date, the POCL algorithms cannot match the efficiency of the so-called industrial-strength planners such as SIPE [16, 17] and O-Plan [4, 14]. Flaw selection strategy has been shown to have a significant effect on the efficiency of POCL planning algorithms, and thus researchers have viewed the design of improved flaw selection strategies as one means of making POCL planning algorithms more practical.

In the current project, we completed an extensive experimental study of the relative performance of the main control strategies that have been proposed in the prior literature for partial-order causal-link planning. Our results are presented in [12], in which we review the literature on flaw selection strategies, and present new experimental results that generalize the earlier work and explain some of the discrepancies in it. In particular, we describe the Least-Cost Flaw Repair (LCFR) strategy developed and analyzed by Joslin and Pollack [8], and compare it with other strategies, including Gerevini and Schubert's ZLIFO strategy [6]. LCFR and ZLIFO make very different, and apparently conflicting claims about the most effective way to reduce search-space size in POCL planning. We resolve this conflict, arguing that much of the benefit that Gerevini and Schubert ascribe to the LIFO component of their ZLIFO strategy is better attributed to other causes.

More specifically, we showed that neither the LCFR nor ZLIFO flaw selection strategy consistently generates smaller search spaces, but that by combining LCFR's least-cost approach with the delay of separable threats that is included in the ZLIFO strategy, we obtain a strategy—LCFR-DSep—whose space performance was nearly always as good as the better of LCFR or ZLIFO on a given problem. We therefore concluded that much of ZLIFO's advantage relative to LCFR is due to its delay of separable threats rather than to its use of a LIFO strategy. Although we were unable to resolve the question of whether least-cost selection is required for unforced, as well as forced flaws, we found no evidence that a LIFO strategy for unforced flaws was better. On

the other hand, separable-threat delay is clearly advantageous.

We also considered the question of computation time, and showed that often LCFR-DSep only requires computation time comparable to that of ZLIFO. LCFR-DSep can therefore be seen as paying for its own computational overhead by its search-space reduction.

These conclusions, however, are tempered by the fact that for certain clusters of problems, our combined strategy, LCFR-DSep, does not generate minimal search spaces. In sum, as a result of our experiments we now understand the reasons that LCFR and ZLIFO perform the way they do, and how to combine the best features of both to create good default strategies for POCL planning. At the same time, it is clear that certain domain-dependent characteristics such as those we identified in several of the domains we studied must still be taken into account in settling on a flaw selection strategy for any particular planning domain.

3 Search Control for Conditional Planning

Conditional planning is an important extension to traditional planning. Conditional planners allow for conditional actions with multiple possible outcomes and for sensing actions that allow agents to determine the current state[1, 5, 7, 3]. A key question in conditional planning is: how many, and which of the possible execution failures should be planned for? One cannot, in general, plan for all the failures that can be anticipated: there are simply too many. But neither can one ignore all the possible failures, or one will fail to produce sufficiently flexible plans. Essentially, this question can be viewed as one of search control: which portion of the plan space should be searched first, to provide the highest-quality contingency plans?

In the current project, we developed Mahinur, a probabilistic partial-order planner that supports conditional planning with contingency selection; our work on this is reported in [10]. Mahinur implements an iterative refinement planning algorithm that identifies the contingencies that contribute the most to the plan's overall value, and gives priority to the contingencies whose failure would have the greatest negative impact. We concentrated on two aspects of the problem, namely, planning methods for an iterative conditional planner and a method for computing the negative impact of possible sources of failure.

We conducted experiments with reasoning aboutthe first implementation

of Mahinur, and compared its performance to other probabilistic conditional planners, notably the C-Buridan [5] system, the best-known alternative for partial-order contingency planning. Mahinur differs from C-Buridan and other earlier systems in explicitly calculating the expected value of handling alternative contingencies at plan time. Our experiments showed that these calculations result an a significant increase in Mahinur's planning efficiency, relative to C-Buridan. We are continuing to work on the Mahinur system, incorporating methods for reducing the probability of failure by adding more supporting actions, and implementing a much larger real-world domain to use as the basis of extended experimental analyses.

4 Monitor-Selection in Planning

A further extension to planners is required when agents in situated in dynamic environments. There, a central challenge is to be appropriately sensitive to changes in its environment. In general, it is too costly to be responsive to every environmental feature that the agent knows about. On the other hand, an agent that is completely unresponsive may fail to take advantage of circumstances that can improve its plans and/or shorten its planning time considerably. The need to balance sensitivity to environmental change against appropriate stability of the plans being formed is strongly reminiscent of the ideas that led to the design of the IRMA architecture and filtering strategy in our earlier work [2].

In recent work on this project, we have introduced the idea of *rationale-based monitoring*, reported in [15]. In this approach, planning is strongly identified as a decision making process and the planning system records the rationale for the choices it makes. Even when planning consists mainly in task decomposition, it will typically involve choosing between alternatives, and the reasons for those choices constitute the plan rationale. The agent can then focus its attention on those changes in the environment that would affect the truth-value of the planning rationale.

A novel aspect of our approach is that we not only monitor features of the world that affect the current plan, but also features of the world that played a role in the decision to select that plan over alternative possibilities. We maintain two sets of monitors: plan-based and alternative-based. Every time the agent needs to make a decision among alternatives, it deliberates and selects

a particular plan. The selected plan gives rise to the plan-based monitors. At the same time, the alternatives considered give rise to alternative-based monitors. As the world state is dynamically changing, the agent remembers alternatives that it judged less valuable, monitoring the world state to see if that judgement should be changed. We implemented a prototype version of rationale-based monitoring and conducted preliminary experiments showing that it can lead to improved plans without significant overhead.

5 Project-Supported Publications[1]

1. Eithan Ephrati, Martha E. Pollack, and Marina Milshtein, "A Cost Directed Planner: Preliminary Report," in *Proceedings of the 13th National Conference on Artificial Intelligence*, pp. 1223-1228, 1996.

2. David Joslin and Martha E. Pollack, "Is 'Early Commitment' in Plan Generation Ever a Good Idea," in *Proceedings of the 13th National Conference on Artificial Intelligence*, pp. 1188-1193, 1996.

3. Martha E. Pollack, David Joslin, and Massimo Paolucci, "Flaw-Selection Strategies for Partial-Order Planning," *Journal of Artificial Intelligence Research*, 6:233-262, 1997.

4. Nilufer Onder and Martha E. Pollack, "Contingency Selection in Plan Generation," in *Proceedings of the Fourth European Conference on Planning*, Toulouse, France, Sept. 1997.

5. Nilufer Onder and Martha E. Pollack, "Contingency Selection in Plan Generation," in *1996 AAAI Fall Symposium on Plan Execution*, Boston, MA, Nov. 1996. (This is a preliminary version of the previous reference.)

6. Nilufer Onder and Martha E. Pollack, "Handling Contingency Selection Using Goal Values," in *1997 AAAI Workshop on Abstractions, Decisions, and Uncertainty*, Providence, RI, July, 1997.

7. Yagil Ronen, Daniel Mosse', and Martha E. Pollack "Value-Density Algorithms for the Deliberation Scheduling Problem," to appear in *IEEE Expert*, 1998.

8. Manuela M. Veloso, Martha E. Pollack, and Michael T. Cox, "Rationale-Based Monitoring for Continuous Planning in Dynamic Environments" to appear in *Proceedings of the Fourth International Conference on AI Planning Systems*, June, 1998.

[1] The first two papers listed were completed prior to the start date of the current contract, and thus do not acknowledge this contract. However, they are both within the scope of the current effort, and follow-on work, which was reported when the papers were presented at the conference, was done during the current contract period.

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